

Crab pulsar spectrum: a non-extensive approach

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Abstract :

Non extensive statistical physics has been applied to various problems in physics including astrophysics. In this paper we explore the possibility of using non extensive approach to explain the recently observed pulsed γ -ray from Crab pulsar above 100 GeV observed by VERITAS γ -ray telescope.

Motivation :

The recent detection of pulsed γ -ray above 100 GeV from Crab pulsar [1] by VERITAS γ -ray telescope can not be explained by standard pulsar models and data has been parametrized by broken power law instead of standard model of power law with exponential cutoff. CRAB is a supernova remnant which emits in radio, optical, x-ray and soft γ -ray wavelengths. In the present paper we explore the possibility of using non extensive form of power law with exponential function to parametrize the CRAB pulsar spectrum. Non-extensive statistical physics has been used to explain anomalous results observed in various problems in physics [2-8]. Non-extensive features get manifested in those systems which have long range forces, long memory effects, inhomogeneous systems or in those systems which evolve in (non Euclidean like space-time) fractal space time [8 and reference therein].

Non-extensive statistical physics has been applied to various astrophysics

problems also. It has been shown that galaxy distribution [9] follows non extensive statistical physics. Tsallis et. al. [10] studied links between various astronomical phenomena and non extensive statistical physics. Luis et. al. [11] used non-extensive approach to study galactic halos of self gravitating systems. Due to long range nature of gravity, self gravitating systems follow non extensive statistics and Juilin [12] obtained non extensive form of Maxwellian distribution which is applicable to astrophysical environments. Chavanis et. al.[13] used non extensive approach to investigate non linear stability of stars and galaxies. Armondo et. al. [14] has shown that the distribution of temperature fluctuations in cosmic microwave background follows non extensive form of Gaussian distribution to the confidence level of 99 %. Using non extensive form of velocity distributions, Chavalho et.al. [15] studied rotational velocities of more than 1600 F and G dwarf stars.

Non extensive statistical physics has been used to derive the density distribution of large scale astrophysical structures and derived profiles have perfect match [16] with the profiles obtained from simulated dark matter and hot plasma distributions. Non extensive approach has also been used to study density profile of simulated galaxy sized dark matter haloes [17]. It has been shown that solar corona dynamics has non Gaussian and non extensive [18,19] statistical character and anomalous diffusion of electron and proton in solar core plasma can be explained by non extensive approach. The study of scale dependence of intermittent flows in astrophysical plasma turbulence which arises due to long range interactions [20] can be explained using non extensive approach. V.M.Vasyliunas [21] used Kappa distributions to account for high energy tail velocity distributions of electrons and ions in space plasma. The link between Kappa distributions and velocity distributions of non extensive nature was established by Leubner [22] resulting in to the theoretical justification of Kappa distributions in the astrophysical plasma. One of the important features of astrophysical plasma is the non Maxwellian core-halo electron and ion velocity distributions and non-extensive approach [23] has been used to explain the results.

non-extensive approach:

Standard Statistical Physics (Boltzmann-Gibbs thermostatics) holds as long as thermodynamic extensivity (additivity) holds i.e. when (a) effective microscopic interactions are short range and (b) systems evolve in Euclidean like space-time (a continuous and sufficiently differentiable) For two systems A and B entropy is additive

$$S(A + B) = S(A) + S(B) \quad (1)$$

Boltzmann-Gibbs(BG)entropy is additive and extensive. BG approach fails (a) in systems with long range forces or long memory effects (b) or if systems evolve in non Euclidean space-time(i.e. fractals or multifractals). Such systems which do not follow Boltzmann-Gibbs approach are called as non-extensive systems [7 and references therein]. For two systems A and B in non extensive approach

$$S(A + B) = S(A) + S(B) + (1 - q)S(A)S(B) \quad (2)$$

where q is non extensive index. Non-extensive statistics is based on two postulates of entropy and internal energy. Non-extensive entropy [7] is defined as

$$S_q = \frac{1 - \sum_i P_i^q}{q - 1} \quad (3)$$

In the limit of $q \rightarrow 0$, entropy is given as

$$S = -k p_i \ln p_i \quad (4)$$

which is Boltzmann-Gibbs Shannon entropy. In non-extensive approach exponential function is written as

$$e_q^{\pm x} = [1 \pm (1 - q)x]^{\frac{1}{1-q}} \quad (5)$$

Crab Pulsar results :

In recent discovery of 100 GeV energy from the CRAB, curvature radiation process has been ruled out as a possible mechanism. It has been argued that inverse Compton process may be responsible for high energy emission from CRAB pulsar. Inverse Compton scattering is very important process for γ -ray

production in astrophysics. In this process low energy photon interaction with relativistic electrons leads to boosting of low photon energies to high energies in various astrophysical environments like pulsars, active galactic nuclei, supernova remnants, cluster of galaxies etc. Lyutikov et. al. [24,25] have shown that inverse Compton effect is the main emission mechanism for CRAB spectrum with non-exponential cutoff. Lefa et. al. [26] have discussed shape of radiation distributions due to inverse Compton in various scenarios including Klein-Nishina regime. In this regime upscattered photons pick up almost all the energy of the relativistic electrons.

The study of electromagnetic radiation from CRAB pulsar has attracted attention in all energy ranges. It began with COMPTEL (Imaging Compton telescope) and EGRET (Energetic γ -rays Experiment Telescope) [27] observation. COMPTEL detected signal from CRAB pulsar from 1 to 30 MeV range. The EGRET measured γ -ray spectrum of CRAB pulsar from 30 MeV up to 5 GeV energy which followed power law spectrum $F(E) \propto E^{-\alpha}$ where $\alpha=2.022 \pm 0.014$ where F is flux. Pulsar emission energy spectrum are described by a generalized form

$$F(E) = A \left(\frac{E}{E_c} \right)^{-\alpha} \exp \left[- \left(\frac{E}{E_c} \right)^\beta \right] \quad (6)$$

where A is the normalized constant, E_c is the cutoff energy and β describes the steepness of the cutoff. However, up to 5 GeV no cutoff in energy spectrum of CRAB pulsar was observed by EGRET. The observation of CRAB pulsar by MAGIC telescope resulted in signal above 25 GeV and measured flux was several times lower than the flux measured by EGRET which signalled the appearance of cutoff. A joint fit of data obtained in different energy ranges like 1-30 MeV from COMPTEL, 30 MeV to 10 GeV from EGRET data and MAGIC data above 25 GeV was observed to follow power law with exponential cutoff. It was further reported that there is similarity in EGRET data and Fermi-LAT data on CRAB pulsar. VERITAS observations on CRAB pulsar in 100 GeV region provided additional data to study its energy spectrum. Joint fitting of Fermi-LAT data, MAGIC data and VERITAS data by power law with exponential

cutoff produced high value of $\chi^2 = 66$ for 16 degrees of freedom. Broken power law fit to the data has χ^2 value of 13.5 for 15 degrees of freedom. Now we explore the possibility of using non extensive form of power law to fit to CRAB pulsar data.

Non extensive form of equation (6) can be obtained by Using equation (5) in equation (6), we have

$$F(E) = \frac{dN}{dE} = A \left(\frac{E}{E_0} \right)^{-\alpha} \left[1 - (1 - q) \left(\frac{E}{E_c} \right)^\beta \right]^{\frac{1}{1-q}} \quad (7)$$

We have used equation(7) to fit to the data of CRAB spectrum over the whole energy range (COMPTEL, EGRET, MAGIC and VERITAS) data as shown in figure 1. We have used gnuplot to fit equation (7) by initially fixing $q=1.2$. The CRAB pulsar data over whole energy range has been fitted by allowing A , E_0 , α , E_c , β and q as variables. The final values are $E_c = 551.562$ MeV, $A = 3.67487 \times 10^{-5}$, $\alpha = -0.413736$, $E_0 = 1.43185$ MeV, $\beta = 0.57564$ and $q = 1.2$. For this case of fitting, the degrees of freedom are 7, the rms of residuals is 0.9249 and the variance of residuals (reduced χ^2) is equal to 0.85544.

Pulsars are rotating magnetized neutron stars with corotating magnetosphere where charged particles are accelerated to relativistic energies. Lyutikov [24,25] have shown that in the case of CRAB pulsar, scattering may happen from dense secondary plasma in deep Klein-Nishina regime where inverse scattered photon may provide direct measurement of particle distribution within the magnetosphere. The spectral energy distribution of observed photons is dependent on the energy distribution of relativistic electrons and it may be possible that velocities of the relativistic electrons may be following non-extensive Maxwellian distribution.

Various anomalous results observed in astrophysical plasma have been resolved by using non extensive approach. Ferro et. al.[28] studied non extensive resonant reaction rates in astrophysical plasma's in detail. Soares et. al.[29] discusses the superiority of non-extensive Maxwell velocity distribution over standard Maxwell velocity distribution for the case of rotational velocities of stars in Pleiadus open clusters. Freitas et. al.[30] studied evolution of F and G

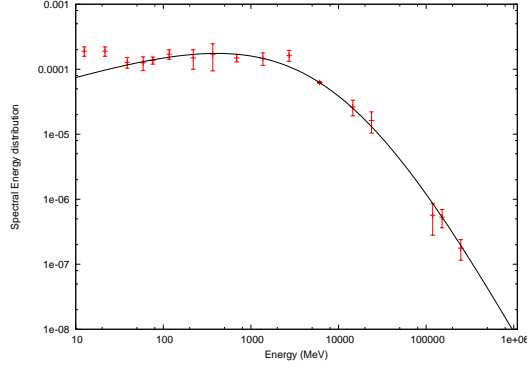


Figure 1: Parameterization of spectral energy distribution is shown of crab pulsar data. The fit corresponds to equation (7) for $q=1.2$

stars and angular momentum loss by magnetic stellar wind with non extensive statistical physics. In an interesting studies Saxena et.al.[31] derived astrophysical thermonuclear functions both for Boltzmann Gibbs statistics and for non extensive statistics and it was observed the cut off at higher energies can be explained better by non extensive approach.

Non-extensive power law arises due to some inhomogeneity in physical systems. Non-extensive distributions have been obtained using Langevin equation with temperature fluctuation or multiplicative noise which are important factors in condensed matter physics. However in astrophysical situations which involve long range interactions, multiplicative noise or fluctuations in temperature may not be factors responsible for inhomogeneity. In recent paper which is of relevance to astrophysics, Zheng et. al.[32] has proposed mechanism which leads to non extensive power law distribution in self gravitational systems. In this mechanism inhomogeneity arises due to inhomogeneity of phase space of self gravitational systems and its momentum space. The inner friction force and momentum are important factors in astrophysical situations because inner friction coefficient is related to the kinetic energy of the particle.

Conclusions:

In this paper we have shown that Crab pulsar spectrum can be explained by using non-extensive approach. This scenario may arise due to non-extensive

nature of the Maxwellian distributions of the velocities of the relativistic electrons.

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